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Reflectometer units for short-wave senders

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THE BRITISH BROADCASTING CORPORATION

RESEARCH DEPARTMENT

REFLECTOMETER UNITS FOR SHORT-WAVE SENDERS

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It uses SI units in accordance with B.S. document PD 5686.

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(RA-95)

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REFLECTOMETER UNITS FOR SHORT-WAVE SENDERS

Summary

Reflectometer equipment has been developed for use on 100 kW and 250 kW high-frequency (h.f.) senders. The equipment provides indications of carrier power, reflection coefficient, unbalanced-to-balanced power ratio, and peak values of maximum line voltages. Trip setting and logic circuits are provided to give increased protection to the senders during normal operation. Eight units have been provided for the Far Eastern Relay Station at Tebrau.

1. Introduction

The external service of the BBC is currently installing new 100 kW and 250 kW senders at the Tebrau transmitting station. It was desired to include monitoring equipment at the transmitter outputs over and above the standard metering offered by the manufacturers which would give protection to the feeders and transmitters, especially during unmanned operation. A complete reflectometer equipment for high-power short-wave senders was therefore developed and eight units have been manufactured, tested and shipped to the transmitting station. Four of these will be fitted to 250 kW and four to 100 kW senders.

At h.f. stations the feeder systems are normally balanced, and modern BBC practice is to enclose feeders inside the building and as far as the switching matrix, in 2 ft x 1 ft metal trunking. The feeders extending beyond the switching matrix are not usually screened.

The input to the reflectometer comprises samples of the fields existing on the feeder as close as possible to the output of the transmitter. It was convenient to incorporate sampling couplers into one wall of the trunking near to the transmitter. In order to avoid interference from high r.f. fields in the vicinity of the couplers it was decided that detection of the sampled fields should be carried out as near to the coupler outputs as possible. The detected output would then be taken, through screened cable and r.f. filtering, to an indicator and trip unit situated at a convenient place in the transmitter assembly.

To obtain high speed and good sensitivity in the tripping facilities it was decided that solid state circuits should be used to initiate the trips and alarms. Because of the high risk of r.f. interference, the screening of all circuits was given careful consideration from the outset of the design. The units were designed to operate at any frequency in the band 4 – 26 MHz.

2. General requirements

In order to check the performance of the transmitter, feeder and aerial and to protect these adequately the following parameters should be monitored continuously whilst the sender is under power:

(1) The power that the transmitter is feeding to the aerial.
(2) The impedance matching of the line.
(3) The amount of power flowing along the feeder in the unbalanced mode.
(4) The maximum voltage that exists at any point on the line between the two legs of the feeder.
(5) The maximum voltage that exists between any point on the line and earth.

A control system should measure all the above parameters and cause the transmitter to trip when any of these exceeds an unsafe level, thus protecting the whole transmitter/aerial system from the effects of mechanical damage or transmitter malfunction. In practice, as measurements can only conveniently be made at one point on the line, some of the above parameters must be inferred from measurements at that point.

Whilst the couplers themselves may not necessarily be situated at a leg-leg or leg-earth voltage maximum, the value of this voltage can be inferred by adding the magnitudes of the voltages due to the forward and reflected waves, providing that the feeder is uniform. Since the characteristic impedance of feeder for the unbalanced mode changes at the transition from enclosed feeder to open wire feeder, the leg-earth voltages on the open-wire section are not indicated directly. However it is expected that experience will show at what voltages registered on the leg-earth voltmeter the transmitter should trip. Similarly although the unbalanced power in the open section of feeder will not be the same as that measured in the trunking, it is thought that the two will not differ greatly.

3. Description of the equipment

3.1. The coupler and detector unit (Fig. 2)

3.1.1. Couplers and equalisers

In the preliminary stages of design, two types of probe were considered. One comprised a transverse slot cut in the metal screen to sample the magnetic field together with capacity plates projecting into the interior of the screen to sample the electric field. The other consisted of an arrangement of directional couplers. Upon investigation it was found that the output from a slot of reasonable dimensions was too small to meet instrumental requirements. It was decided, therefore, that the reflectometer design should be based on the use of terminated directional couplers.

The general arrangement of the directional couplers in relation to the balanced conductors of the feeder and their connection to balun transformers, equalisers and amplifier/detectors is shown in Fig. 1. Each of the couplers consists of a strip transmission line having a characteristic impedance of 50 ohms, one end being terminated in a 50 ohm resistive load, the other being directly connected to a 50 ohm coaxial output socket.

The two outer pairs of couplers provide coupling to the forward and backward balanced field components and the centre coupler provides coupling to the forward unbalanced wave field components. All couplers are sensitive to the unbalanced and balanced mode of transmission except for the central coupler which is sensitive to the unbalanced mode only. Elimination of the unbalanced mode voltages from the output of the balanced mode couplers is achieved by combining the outputs of pairs of couplers by means of balun transformers as shown in Fig. 1.

The balun transformers have a 1 : 1 turns ratio and hence the matching impedance at the output terminals of the the baluns is 100 ohms. Equalisation is applied, in the case of the balanced mode voltages, to the output of the balun transformers and for the unbalanced mode voltages, directly to the output of the unbalanced mode coupler. Bridged-T networks, having characteristic impedances of 100 ohms and 50 ohms are used for the balanced and unbalanced mode equalisers respectively.

It is arranged that the couplers can be readily removed as separate units from trunking baseplate. The balun transformers and equalisers are self-contained in cast metal boxes which are attached to the amplifier/detector screening case. Interconnection between equalisers and couplers is by way of UR43 cable.

3.1.2. The amplifier/detectors

These units provide amplification, detection and impedance conversion. The output from each equaliser is amplified in a two-stage r.f. amplifier and detected in a single diode mean detector. The voltage on the detector reservoir capacitor is applied to a f.e.t. through a low-pass filter and a final transistor emitter-follower stage giving a d.c. coupled output at low impedance. The output signal comprises the a.c. modulation waveform superimposed on a mean d.c. level proportional to the carrier level of the applied signal. Adjustment of the bias on the f.e.t. gate is provided to ensure that there is zero d.c. input for zero input signal. The gains of the amplifiers are pre-set to give 1 volt d.c. output for 250 kW or 100 kW (depending on the sender output power). The supply voltages for the amplifier/detector units are produced by regulated power supply units which operate from a 50V a.c. mains carried by screened cable from the transmitter unit.

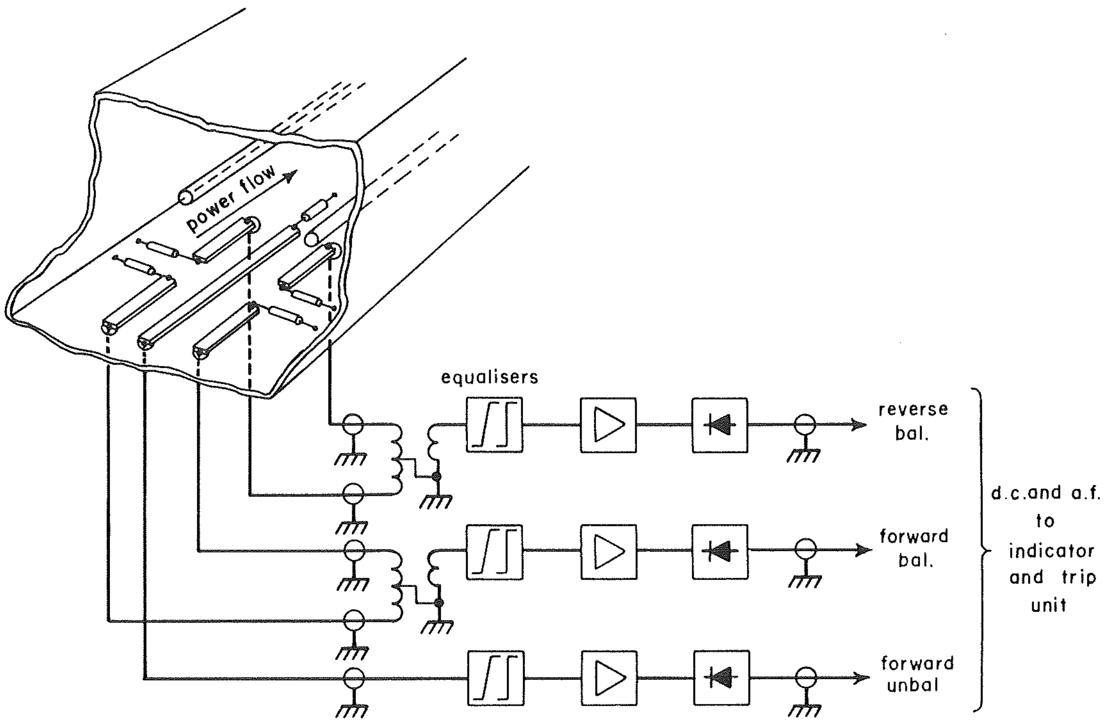
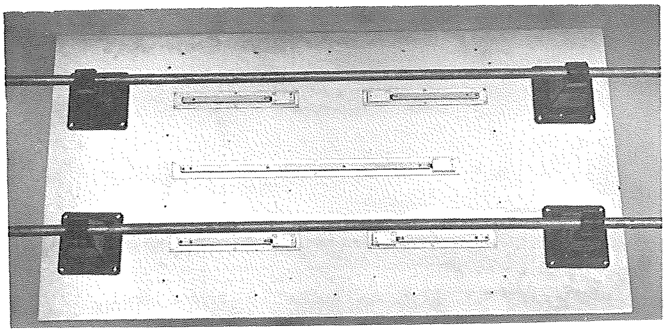
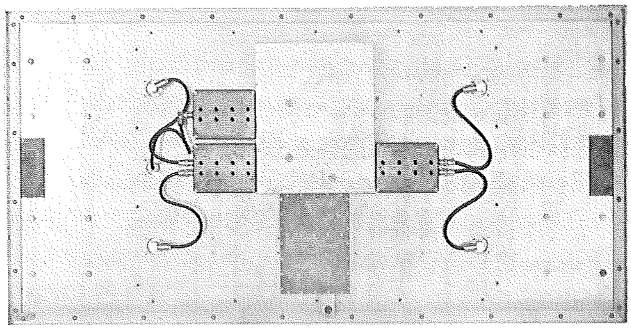


Fig. 1 - Coupler and detector unit: Schematic



(a)



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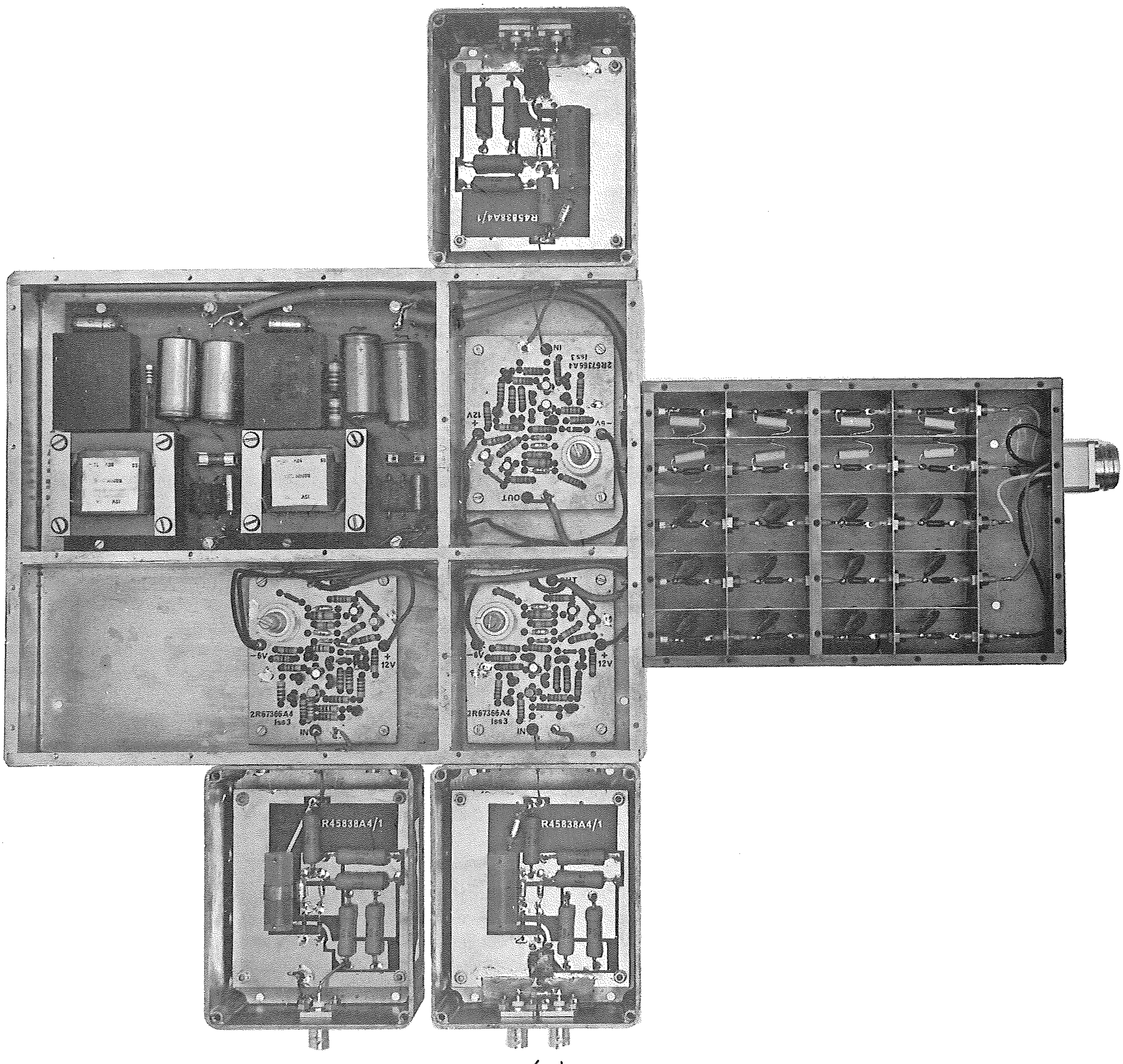


(c)

Fig. 2 - Coupler and detector unit

(*a*) couplers on feeder side of mounting plate (*b*) equalisers, amplifier/detectors and filter on back of mounting plate

(*c*) equalisers, amplifier/detectors and filter with cover removed

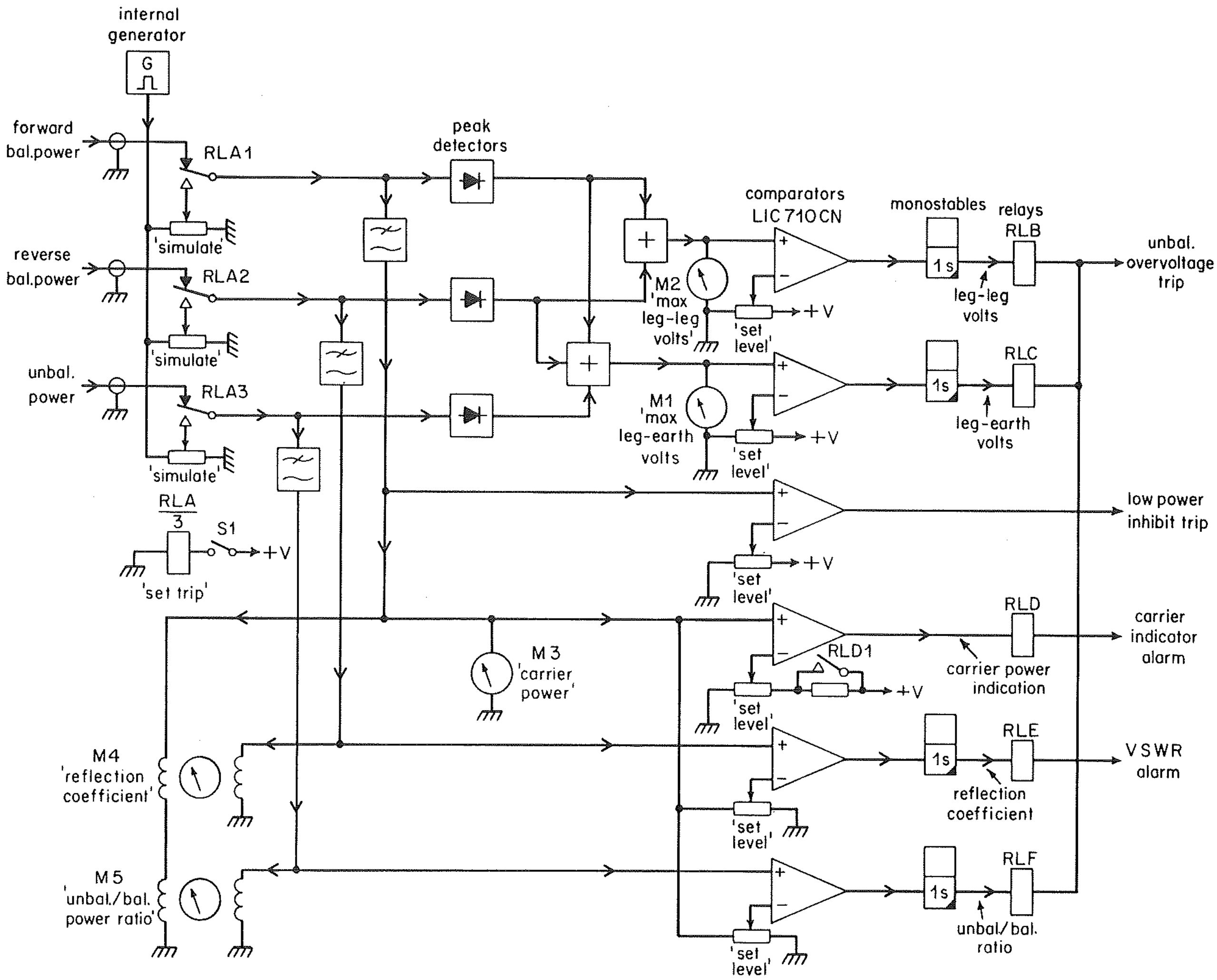


Fig. 3 - Indicator and trip unit: Schematic

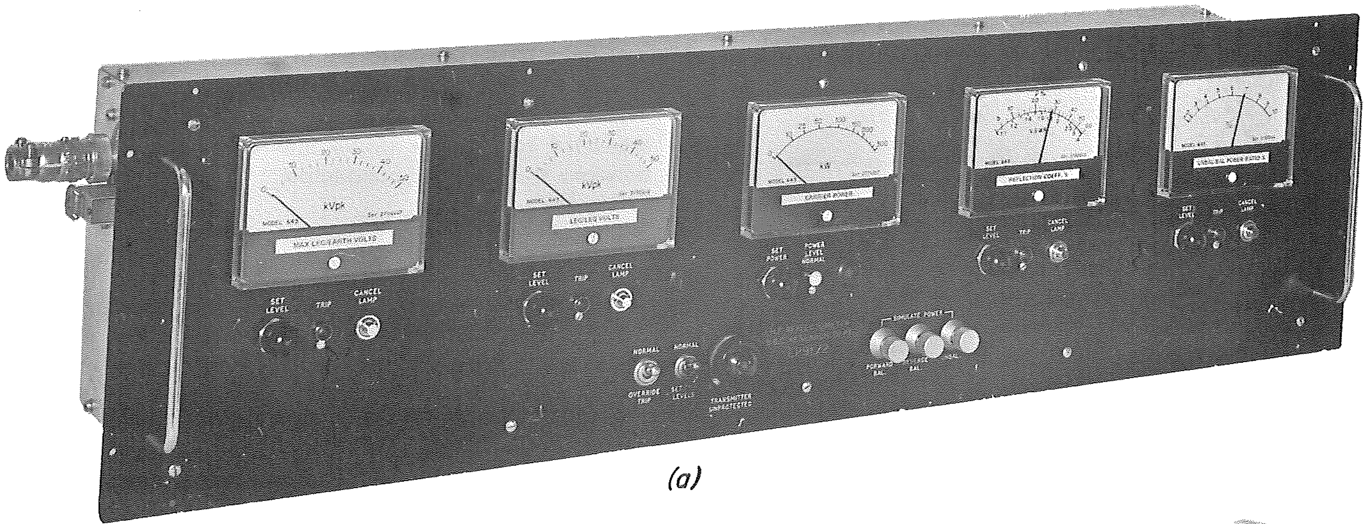
3.2. Indicator and trip unit (Figs. 3 and 4)

The output signals from the amplifier/detectors are passed to this unit through a multi-way screened cable and meter indications and tripping operations are derived from them. Each of the three inputs is applied to a peak detector and a low-pass filter with a long time constant from which d.c. components are obtained. The detector circuit has a fast rise time (less than 100μs) in order to react to rapid voltage peaks. A large detector reservoir capacitor gives the peak voltage a slow decay time to allow the indicating meters to reach peak values.

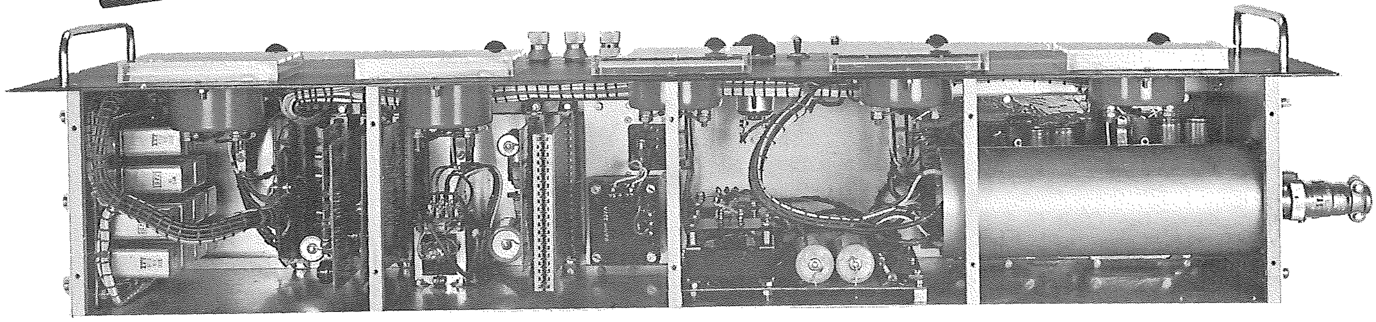
To produce the sums of peak voltages for the maximum leg-leg and leg-earth trips and meters, virtual-earth adders employing an I.C. are used. The resulting sums of voltages are displayed on meters M1 and M2 and also compared (in IC710 comparators) with voltages set up on adjustable potentiometers situated immediately below the meters on the front panel. When the peak voltage signal exceeds the set value the comparator triggers a monostable circuit which activates a relay for about 1 sec. Relays in the transmitter circuits are activated to trip and a lamp is lit to record the cause of tripping. This lamp may be cancelled with a button.

The three remaining meters and trips react to the mean values of the input signals and are fed through low-pass filters. The mean forward balanced power voltage is fed to meter M3 and to the control windings of ratiometers M4 and M5. A comparator inhibits the transmitter from tripping at very low values of forward signal and a further comparator circuit cancels the carrier alarm and lights a lamp when the output carrier power reaches its normal operational value. This second comparator circuit has hysteresis so that once the carrier alarm has been cancelled it will not re-start until the carrier level has dropped by 10%.

The reflection coefficient and unbalanced/balanced metering and tripping circuits are similar. Each of the reverse unbalanced signals is fed to the deflector winding of the relevant ratiometer (meters M4 and M5) and to one input of an IC710 comparator, where it is compared with a proportion of the forward signal (derived from a variable 'set trip' potentiometer below the relevant meter). When the signal exceeds the pre-set fraction of the forward balanced signal the comparator initiates a 1 sec pulse to activate the appropriate transmitter trip circuits. Similarly an alarm is given if the unbalanced/balanced power ratio exceeds a pre-set value.



(a)



(b)

Fig. 4 - Indicator and trip unit
(*a*) front panel (*b*) view from above with cover removed

In addition to the tripping and metering facilities in the unit there is also an output of programme, derived from the forward balanced coupler and amplified, for monitoring purposes.

4. Calibration and adjustment of the equipment

4.1. Directional coupler adjustment and calibration

The maximum output from the balanced directional coupler pairs was limited in the design by the maximum power which could be handled by the balun transformers which are incorporated in the equaliser network. This was a maximum of 4 watts mean power at the high frequency end of the band. The initial dimensions for the directional couplers were based on formulae derived by Oliver.[1] Those were for coupled lines having cylindrical cross-section conductors and provided a starting point for the experimental determination of dimensions for directional couplers consisting of strip conductors having finite thickness.

An 8 m (24 ft) length of trunking complete with balanced conductors, was available for test purposes: a series of holes were drilled along its wall to permit the insertion of a capacitive probe into the interior and hence the standing wave ratio existing on the line to be measured.

To measure a high coupler directivity (up to −40 dB) the test line load impedance should be at least 0·98 SWR relative to the test line characteristic impedance and to achieve a wide bandwidth for the coupler directivity, the characteristic impedance of the coupler line should be close to the value of its terminating loads. Coupler adjustment was effected at 15 MHz by varying the separation between the coupler line and baseplate until a high apparent directivity had been obtained. The resulting characteristic impedance of the coupler line was determined from time-domain reflectometer measurements. By modifying the coupler line conductor dimensions and repeating the measurement process, an apparent directivity of −55 dB and a coupler line impedance within 2% of the coupler terminating loads was obtained. At other frequencies, the measurements were made using pairs of couplers with the outputs combined through a balun transformer, this gave discrimination against possible errors resulting from the presence of unbalanced mode voltages on the test line.

Below 10 MHz the line length was too short to make accurate SWR measurements and matching was carried out using a bridge. The directivity of the couplers was assessed by including the value of reflection coefficient determined from SWR measurements on the test line with the apparent directivity derived from the coupler measurements. Fig. 5 shows the estimated directivity of the couplers. The output ratio of the coupler was measured with a vector voltmeter, the reference channel probe measuring the voltage developed across one half of the balanced load terminating the test line and the other probe measuring the output from the forward wave couplers. The mismatch produced by the

presence of the reference probe across test line load was eliminated by tuning out the probe self-capacitance with a shunt inductor.

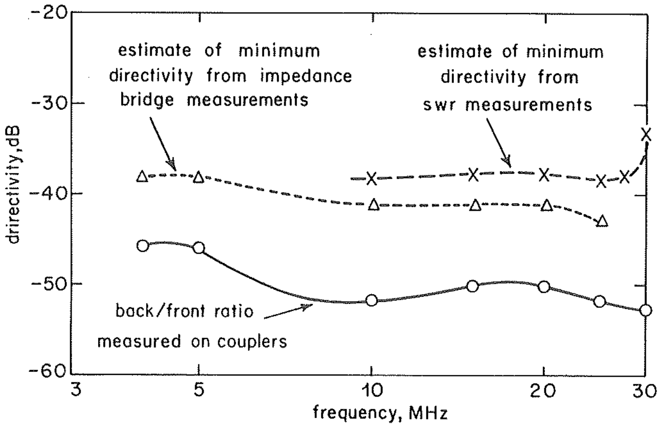


Fig. 5 - Directivity of balanced mode couplers

The results of these measurements were subject to error because of the difference in impedance levels at the two probe points, (i.e. 328 Ω and 50 Ω) and as a further check, the test line was terminated with λ/2 line balun the output of which was attenuated until its amplitude was the same as that obtained from the forward couplers. The output ratio was obtained from the value of added attenuation plus a correction for mismatch loss on the test line, the latter being derived from the reflection coefficient measured with the aid of the coupler outputs.

Similar measurements were made for the unbalance-mode coupler, the measured output ratio characteristics are shown in Fig. 6.

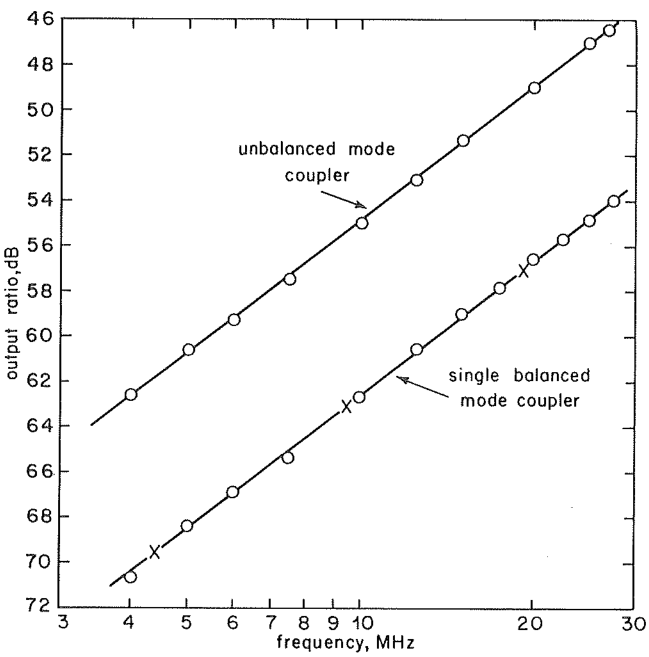


Fig. 6 - Output of couplers

O Tuned load measurements

x λ/2 line balun measurements

The unbalanced-mode coupler is dependent on its symmetry with respect to the balanced line conductors for its discrimination against balanced mode voltage coupling. The coupling figure for this voltage was computed and measured for coupler displacement from the central axis between the balanced conductors. The results are shown in Fig. 7.

The curves show the coupling of the balanced mode voltage into the unbalanced coupler relative to that coupled into a single balanced coupler.

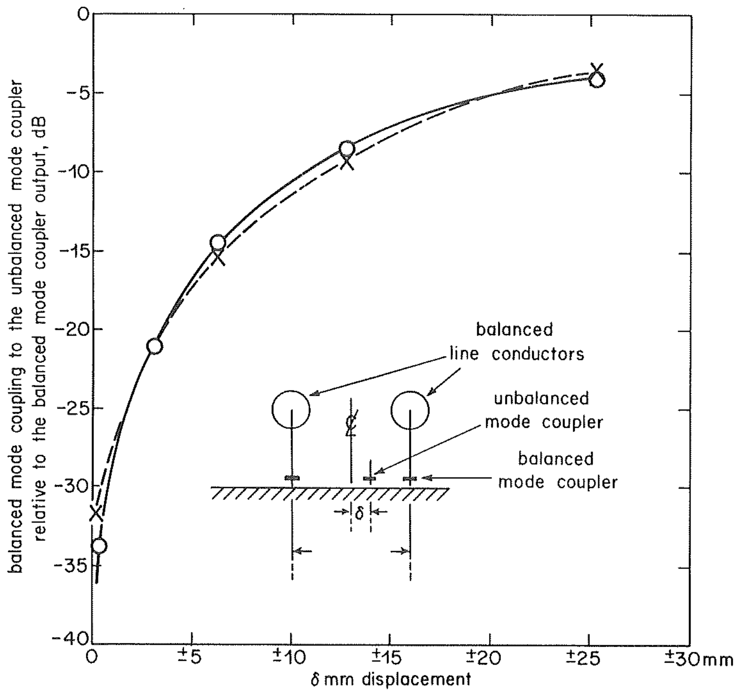


Fig. 7 - Rejection of balanced mode by unbalanced-mode coupler

—O— Theoretical curve —X— Measured curve

4.2. Equaliser adjustment

The equalisers, when fed from the outputs of the forward balanced couplers, were adjusted to give an overall flat frequency response relative to the voltage developed across the test line load, the procedure for measurement being the same as that described in Section 4.1 – for the measurement of coupler output ratio.

Compensation for deviation from the required frequency response caused by imperfect performance of the balun transformer and network components, is provided at low frequencies by the addition of capacitance in series with the inductive arm of the network and at high frequencies by the addition of resistance in series with the shunt capacitor arm of the network. The addition of the response correction components and the balun transformer characteristics does impair the input impedance of these units; however the matched impedance presented to the coupler is not greater than 0·8 SWR at the lowest frequency.

4.3. Calibration of the amplifer detectors

The amplifier-detectors for forward, reverse and unbalanced power are similar but the gains of the amplifiers are all adjusted to produce 1 volt d.c. outputs for 250 kW (or 100 kW), 60% voltage reflection coefficient and 10% unbalanced power. This is so that the unbalanced power and reflected power detectors are working at the most linear part of their range. By keeping signal levels relatively high in the connecting leads to the indicator unit, the effects of interference are reduced.

The R.F. response of the amplifiers is sufficiently flat over the band to introduce no appreciable error over and above the errors in the rest of the system.

The calibration of the whole of the reflectometer r.f. system could not be performed at the same time because of the limited r.f. power available for this purpose. Final testing was carried out by driving the inputs to the balun/equaliser units with known input powers from a well matched source. This was achieved by feeding a balanced source of up to 20 watts r.f. output through 10 or 20 dB attenuators to the input connectors of the equaliser units. The output level from the source was adjusted until the output level from the amplifier/detector was 1 volt d.c. The attenuators were then disconnected from the equaliser inputs and the power measured with a milliwattmeter. The gain of the amplifier in amp/det. unit was adjusted until the measured power input level to the equaliser was at the required level. Typical response curves measured in this way, corrected for the directional coupler response, are shown in Fig. 8.

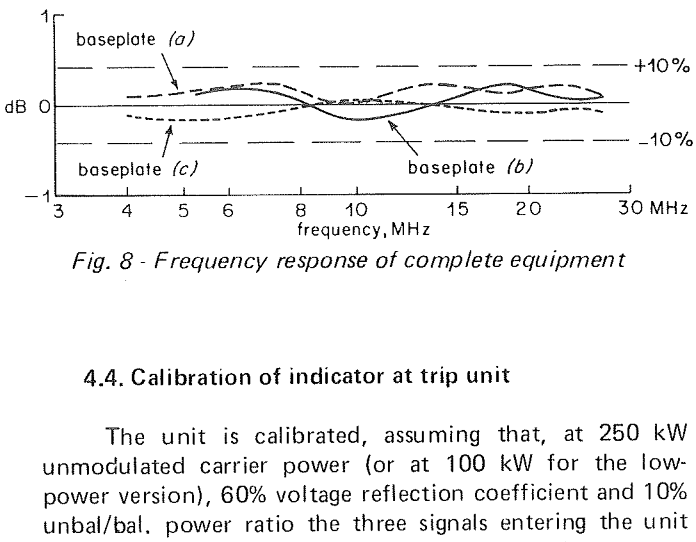


Fig. 8 - Frequency response of complete equipment

4.4. Calibration of indicator at trip unit

The unit is calibrated, assuming that, at 250 kW unmodulated carrier power (or at 100 kW for the low-power version), 60% voltage reflection coefficient and 10% unbal/bal. power ratio the three signals entering the unit will each be +1V d.c. Series and shunt resistances are adjusted for meters M3, M4 and M5 to produce 250 kW, 60% and 10% readings respectively for 1V applied in each case. The peak voltage readings are adjusted by suitable choices of weighting resistors in the circuit producing the sums of V_{pk} (forward), V_{pk} (reverse) and V_{pk} (unbal.).

The tripping circuits require no calibration as the tripping levels are all set by referring to readings on the meters which have been calibrated.

As the coupler and meter units are calibrated independently, units calibrated for the same power range are interchangeable.

5. Alarm and trip level setting

To set an alarm or tripping value, the inputs from the couplers are replaced by three internally generated signals by setting a switch to 'SET TRIP LEVELS'. The levels of the three 'simulate power' signals are varied by three potentiometers on the front panel and combinations of the three signals may be used to produce any desired readings on the meters. When a meter reads the required level the relevant 'SET LEVEL' control is turned until the corresponding lamp lights. When the 'SET TRIP LEVELS' switch is returned to 'NORMAL' the alarm or trip will occur when this set level is exceeded. Whilst the tripping and alarm levels are being set the output to the transmitter control circuits are inhibited so that, whilst the transmitter is running, tripping levels may be altered without tripping the transmitter. A warning light tells the operator 'TRANSMITTER UNPROTECTED' whilst the levels are being set. There is also an 'OVERRIDE TRIP' switch which will inhibit the tripping and alarm signals if, for example, the transmitter is to be run under abnormal conditions which would otherwise cause it to trip.

6. Accuracy of indication

6.1. Power indication

In estimating the accuracy of power indication by the reflectometer the errors due to the frequency response of the equaliser/amplifier detector units, measuring accuracy, and dissimilarity of output ratio between the production and prototype baseplate couplers are included. They are ±0·2 dB, ±0·1 dB and ±0·1 dB respectively giving an overall accuracy at full transmitter power of ±0·4 dB i.e. within 10% of the calibrated value. At lower transmitter powers, the calibration is characterised by reduced sensitivity of the detector circuit, the resulting error is the value shown in Fig. 9 ±0·4 dB. The equipment indicates forward balanced power and the net power flow is obtained by multiplying the indicated value by $(1-\rho^2)$ where ρ is the indicated reflection coefficient.

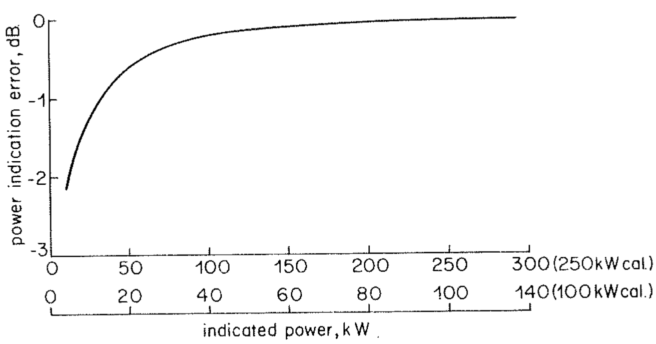


Fig. 9 - Power indication error

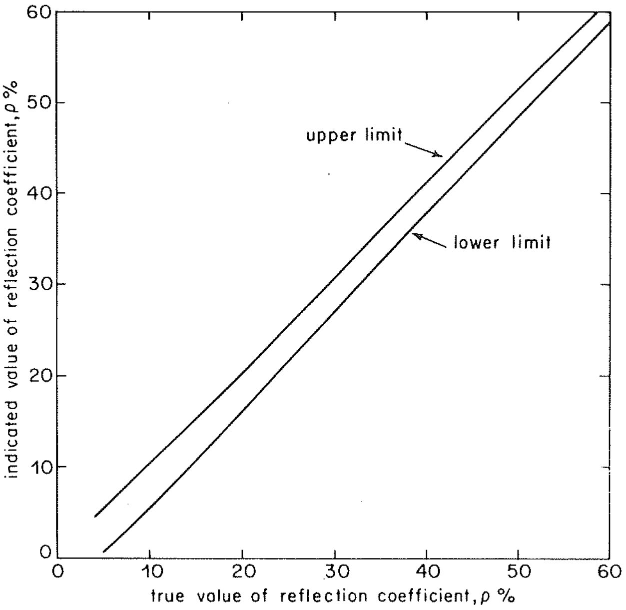


Fig. 10 - Indication of reflection coefficients

6.2. Reflection coefficient

The directivity of the couplers is no worse than 34 dB. Fig. 10 shows the limits within which the true value of reflection coefficient will lie. The errors are due to limited directivity and the detector characteristics.

6.3. Unbalanced power/balanced power ratio

The estimated accuracy is ±8% of full scale deflection.

6.4. Leg/leg and leg/earth volts

The accuracy of the indicated values should be within ±5% and ±3% of full scale deflection for the 250 kW and 100 kW transmitters respectively. However, these tolerances apply to the maximum possible values of line voltage which can occur, and it is possible that the actual line voltages are not as large as those indicated since it has been assumed that balanced and unbalanced mode voltage maximum will occur at the same places, and that the backward unbalanced power flow is equal to the forward unbalanced power flow.

7. Conclusion

Reflectometer units have been developed for the Far-Eastern relay station at Tebrau, which have a useful degree of accuracy and which provide transmitter protection facilities. Care was taken in the design to ensure reliable operation under tropical conditions and it is hoped that these measures will prove to be effective in service.

8. Reference

1. OLIVER, B.M. 1954. Directional electromagnetic couplers. *Proc. Inst. Radio Engrs.*, 1954, **42**, 11, pp. 1686 – 1692.

SMW/JUC

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